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Low-cost monolithic chopper-stabilized op amp with differential input compensates for intermodulation and holds input offset voltage errors to 1 μV over its full operating temperature range.

CMOS chopper op amp does away with glitches

Most data-acquisition systems require operational amplifiers that provide enough inherent dc stability to eliminate tweaking with trimming potentiometers. Conventional op amps that have input offset voltages in the millivolt range approach this requirement, but they still need periodic adjustments. A new monolithic chopper-stabilized op amp, the ICL7650, achieves tweakless performance with a typical input offset voltage of 1 μV or less over its full operating temperature range—and the device sells for only $2.75 in 100-unit quantities.

Fabricated with CMOS technology, the ICL7650 is virtually devoid of the glitches that plague older chopper-stabilized designs, which are derived from vacuum-tube equivalents (see "The Traditional Chopper—and Its Problems"). The ICL7650 depends on just two noncritical external capacitors, rather than on the two low-pass filters, one high-pass filter, and demodulator essential to popular choppers.

Designed for monolithic construction, the ICL7650 circuit (Fig. 1a) consists of a main dc amplifier, a nulling dc amplifier, an output clamp, a compensation circuit that minimizes the intermodulation between applied signals and the chopping frequency, and switches controlled by a two-phase oscillator. These switches are actuated on alternate half-cycles of the chopping frequency.

How the chopper works

A novel chopper-switching arrangement ensures virtually glitchless output. During one clock half-cycle of the oscillator, the A switches close and the B switches open, driving the nulling amplifier to a null (Fig. 1b). A fraction of the voltage on capacitor C_1 is then added algebraically to the input of the nulling amplifier, so as to null the input-voltage offset error of this amplifier.

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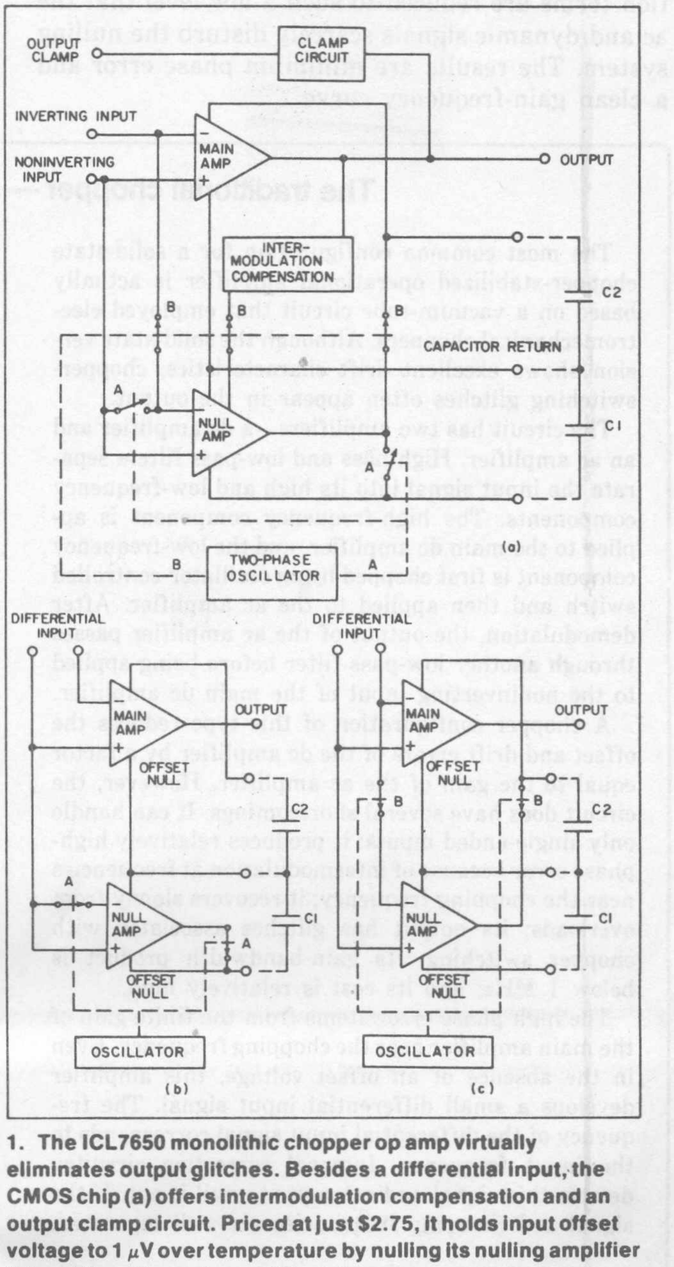


1. The ICL7650 monolithic chopper op amp virtually eliminates output glitches. Besides a differential input, the CMOS chip (a) offers intermodulation compensation and an output clamp circuit. Priced at just $2.75, it holds input offset voltage to 1 μV over temperature by nulling its nulling amplifier (b) and then the main amplifier (c).

In the other clock half-cycle of the oscillator, the B switches close and the A switches open, driving the main amplifier to a null (Fig. 1c). During this clock interval, capacitor C_1 holds the nulling amplifier in its nulled state, while the main amplifier is being nulled. Capacitor C_2 maintains the main amplifier in its nulled state. The null sequence continually repeats, to produce a very low offset voltage.

The ICL7650 minimizes intermodulation effect by generating a compensating dynamic offset in the nulling amplifier when the B switches are closed. Therefore, the nulling amplifier does not see the main-amplifier input signal as an offset error. Although the correction is not total, the intermodulation terms are reduced to such a low level that the ac and dynamic signals scarcely disturb the nulling system. The results are minimum phase error and a clean gain-frequency curve.

A very effective approach prevents input overloads —a clamp in the feedback network reduces the closed-loop gain of the main amplifier just before the circuit reaches its maximum output level. The clamp consists of a pair of low-leakage n and p-channel MOSFETs that turn on shortly before the output limits. The clamp network is brought out to an external pin. Tying this pin to the chip's inverting input implements the clamping automatically. The clamping action does not disturb the null network and has negligible effect on the device's input bias current in the active region.

Besides providing a virtually glitch-free output and very fast recovery from overloads, the ICL7650 offers differential inputs, a maximum phase error of 10 degrees, a gain-bandwidth product of 2 MHz, and a low 100-piece price of $2.75. Furthermore, because the chip is CMOS, its power dissipation is low, with a typical no-load supply current of less than 2 mA.

The traditional chopper — and its problems

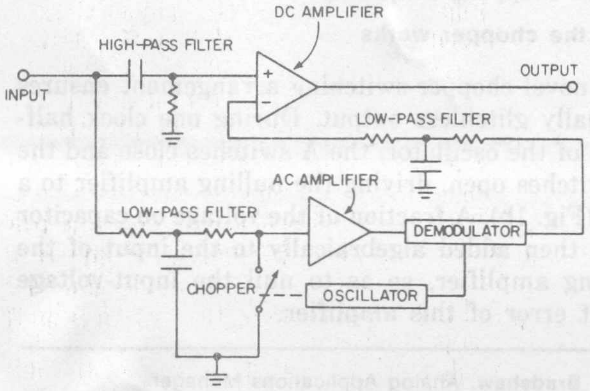
The most common configuration for a solid-state chopper-stabilized operational amplifier is actually based on a vacuum-tube circuit that employed electromechanical choppers. Although the solid-state version shows excellent drift characteristics, chopper-switching glitches often appear in the output.

The circuit has two amplifiers—a dc amplifier and an ac amplifier. High-pass and low-pass filters separate the input signal into its high and low-frequency components. The high-frequency component is applied to the main dc amplifier, and the low-frequency component is first chopped by an oscillator-controlled switch and then applied to the ac amplifier. After demodulation, the output of the ac amplifier passes through another low-pass filter before being applied to the noninverting input of the main dc amplifier.

A chopper configuration of this type reduces the offset and drift errors of the dc amplifier by a factor equal to the gain of the ac amplifier. However, the circuit does have several shortcomings. It can handle only single-ended inputs; it produces relatively high-phase error because of intermodulation at frequencies near the chopping frequency; it recovers slowly from overloads; its output has glitches associated with chopper switching; its gain-bandwidth product is below 1 MHz; and its cost is relatively high.

The high phase error stems from the finite gain of the main amplifier near the chopping frequency. Even in the absence of an offset voltage, this amplifier develops a small differential input signal. The frequency of the differential input signal corresponds to the input frequency. Internal correction circuitry detects this signal and attempts to null it out. If the signal and chopping frequencies are well separated, successive nulling attempts will be weak, or will even cancel each other. However, if the two frequencies are close, the nulling circuit will generate significant beat-frequency terms. As a result, the intermodulation causes excessive phase error, as well as wrinkles in the circuit's gain-frequency curve.

Overload conditions present yet another problem. The feedback network has trouble coping with input signals when the amplifier output hits one power-supply rail or the other. Unless the offset null network recognizes the situation, the overload will be treated as an offset error, and the nulling amplifier will attempt to correct it. Since this attempt is bound to fail, the nulling network will be substantially offset. When the input signal returns to what should be the active region, the false null causes a maximum error, and recovery to a normal condition is very slow. This problem can be controlled if the nulling process is inhibited when the output approaches either supply rail, but leakages in the null network eventually compromise this solution.



Another advantage of CMOS is that the op amp operates from a single 5-V supply, so it is compatible with standard TTL systems. It can also operate with bipolar supplies up to ± 8 V. In either case, the input common-mode range includes the negative supply.

The ICL7650 comes in a choice of two packages and two temperature grades—a 14-pin plastic DIP for operation from 0 to 70°C, a 14-pin ceramic DIP for −25 to +85°C, and an 8-pin TO-99 metal can for operation over either temperature range. No matter the package, the device is internally compensated for unity-gain operation.

The 8-pin version is pin-compatible with standard op amps, except for the null-system capacitors. The 14-pin version provides for an optional external oscillator. The duty cycle for the external oscillator is not critical, because an internal divide-by-two circuit ensures a 50% duty cycle.

Optimum values for the two external capacitors, C_1 and C_2, depend on the chopping frequency. For the preset 100 Hz of the internal oscillator, the best value is 0.1 μF. When an external oscillator is used, this value should change proportionately to maintain the relationship between the chopping frequency and the nulling time constant. A high-quality film capacitor (for example, mylar) is preferable, although a ceramic or other lower-grade type may be suitable in many applications.

Putting the chip to work

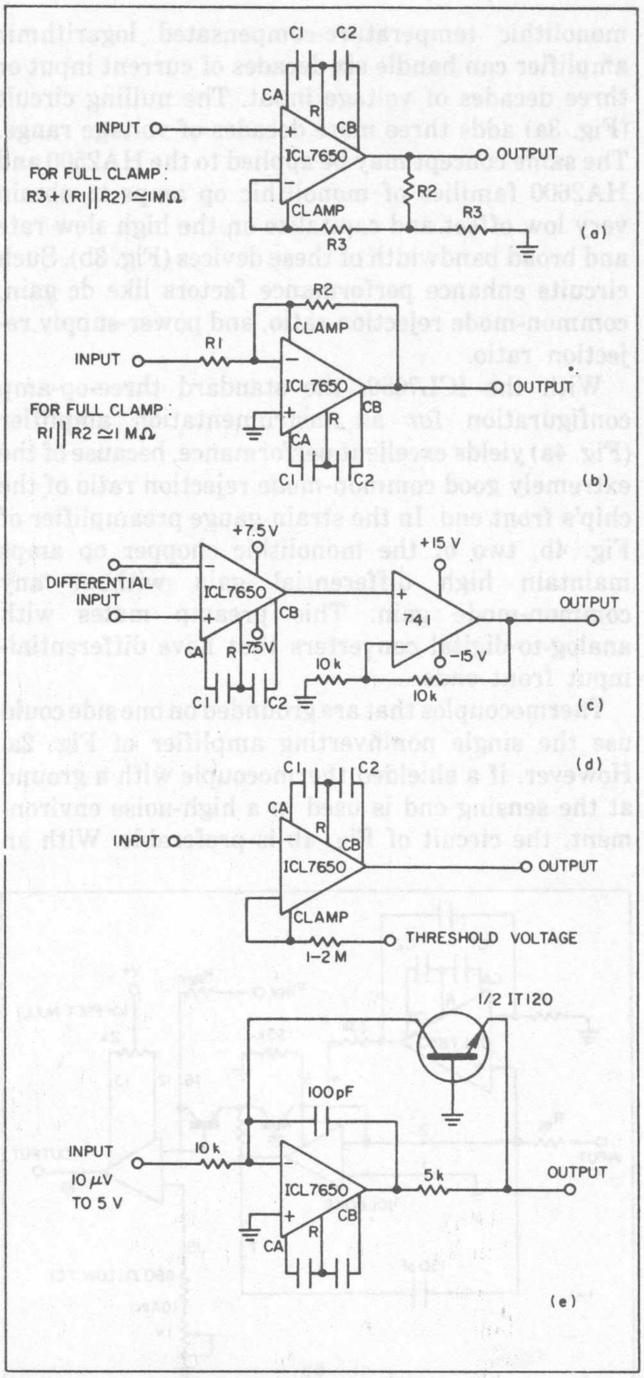
Any application where system performance can be significantly improved by a reduction in input offset voltage and bias current is right for the ICL7650.

Figure 2a shows the basic configuration for a noninverting amplifier with the clamp circuit connected; Fig. 2b shows the inverting configuration, also with the clamp connected. For applications that require output swings greater than ±7.5 V, the booster circuit of Fig. 2c can be used.

In Fig. 2d, the clamp circuit works to advantage in a zero-offset comparator. Here, the problems that usually prevent the selection of a chopper-stabilized amplifier are avoided, because the inverting input of the ICL7650 follows the input signal. The comparator's threshold input must tolerate the output-clamp current without disturbing other portions of the circuit.

The circuit of Fig. 2e illustrates a logarithmic amplifier that has wide dynamic range. Because it avoids the limitations resulting from excessive input offset voltage, it can achieve about six decades of dynamic range in the voltage-input mode. Logarithmic amplifiers built with other devices usually have only a three-decade dynamic range.

The ICL7650 can also provide offset nulling for other amplifiers, such as the ICL8048. This

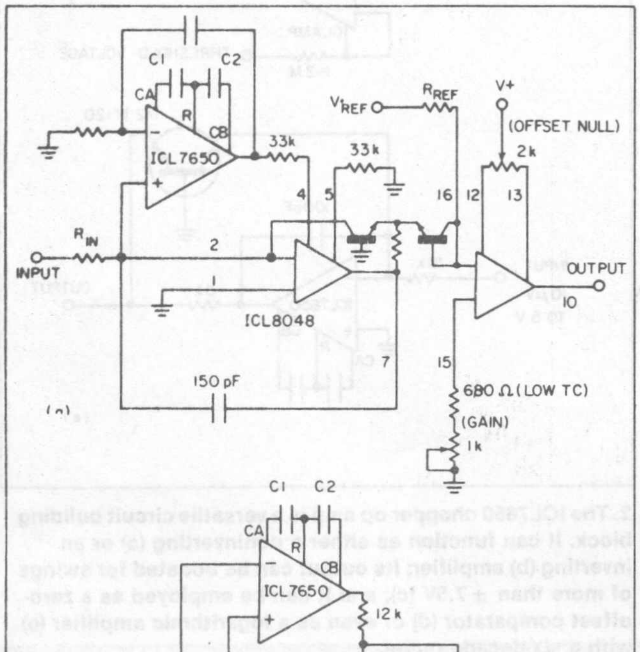


2. The ICL7650 chopper op amp is a versatile circuit building block. It can function as either a noninverting (a) or an inverting (b) amplifier; its output can be boosted for swings of more than ± 7.5V (c); and it can be employed as a zero-offset comparator (d) or even as a logarithmic amplifier (e) with a six-decade range.

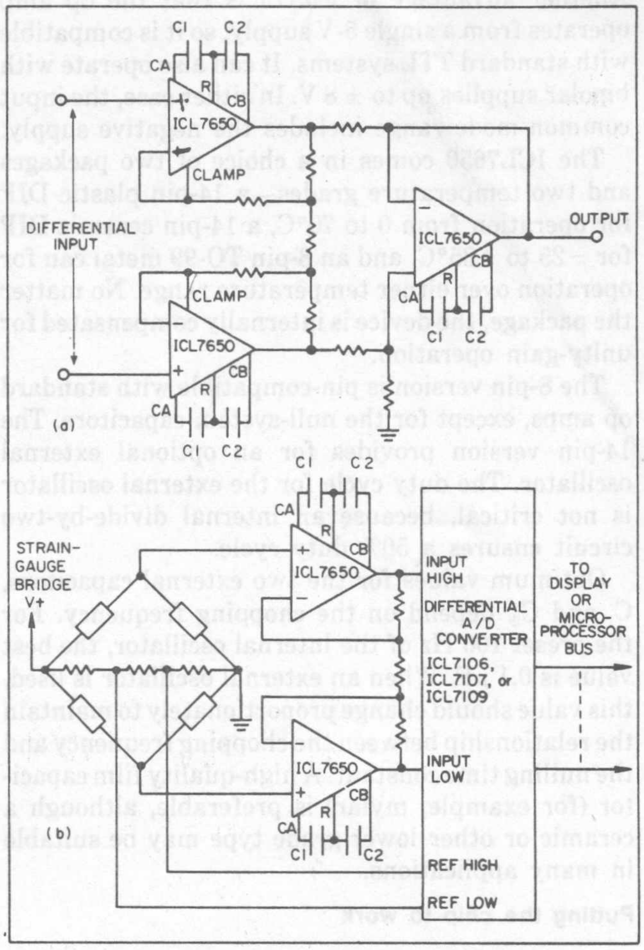
monolithic temperature-compensated logarithmic amplifier can handle six decades of current input or three decades of voltage input. The nulling circuit (Fig. 3a) adds three more decades of voltage range. The same concept may be applied to the HA2500 and HA2600 families of monolithic op amps to obtain very low offset and capitalize on the high slew rate and broad bandwidth of these devices (Fig. 3b). Such circuits enhance performance factors like dc gain, common-mode rejection ratio, and power-supply rejection ratio.

With the ICL7650, the standard three-op-amp configuration for an instrumentation amplifier (Fig. 4a) yields excellent performance, because of the extremely good common-mode rejection ratio of the chip's front end. In the strain-gauge preamplifier of Fig. 4b, two of the monolithic chopper op amps maintain high differential gain without any common-mode gain. This preamp mates with analog-to-digital converters that have differential-input front ends.

Thermocouples that are grounded on one side could use the single noninverting amplifier of Fig. 2a. However, if a shielded thermocouple with a ground at the sensing end is used in a high-noise environment, the circuit of Fig. 4b is preferable. With an



3. The new chip enhances the performance of other amplifiers—for example, nulling the offset for an 8048 log amp (a) or for the 2500/2600 families of op amps (b).



4. Because of its high performance, the ICL7650 has numerous applications—as an instrumentation amplifier (a) with a standard three-op-amp configuration and as a strain-gauge preamplifier (b) for an a-d converter.

absolute platinum-platinum-rhodium (type S) thermocouple, the very low offset and drift errors of the ICL7650 contribute less than 1°C initial error and less than 0.2°C drift error between temperatures of 0 and 1750°C.

The full benefit of the ICL7650's performance can only be realized when care is taken to minimize the introduction of spurious thermocouple voltages between the printed-circuit board, connectors, device sockets, and component leads. Moreover, heat sources must be well removed from critical portions of the circuit, and cooling air should not pass over this critical circuitry after the air has been used or even beforehand, if possible. Even radiated heat can cause problems.□